The Impactor Flux in the Pluto-Charon System

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Abstract: Current impact rates of comets on Pluto and Charon are estimated. It is shown that the dominant sources of impactors are comets from the Kuiper belt and the inner Oort cloud, both of whose perihelion distributions extends across Pluto's orbit. 1,ong-period comets from the outer Oort cloud are a negligible source of impactors. 'l'he total predicted number of craters is not sufficient to saturate the surface areas of the planet or its large satellite. However, heavy cratering may have occurred early in the solar system's history during clearing of planetesimals from the outer planets' zone.

Introduction

The Pluto-Charon binary holds a unique position at the outer edge of the known planetary system, a region it shares with several large cometary reservoirs. As such, cometary impacts have likely played a major role in determining the surface morphology of the planet and its large satellite. Given that a planned spacecraft mission may explore the Pluto-Charon system in detail within the next two decades, it is worthwhile to consider what density and distribution of impacts might be expected on the surfaces of these two bodies.

Prior estimates of cometary impact rates on Pluto and Charon were made by Weissman et al. (1989, hereafter WDS89). They found that impacts by long-period comets from the Oort cloud were fairly negligible, even when cometary showers were included, whereas impacts from the proposed Kuiper belt (Duncan et al., 1988) would be several orders of magnitude greater. in addition, WDS89 made crude estimates of the cratering expected on Pluto and Charon by proto-comets being ejected from the Uranus-Neptune zone during zone clearing early in the history of the planetary system. They found that the total impacts from that source were comparable to the steady-state impacts from the Kuiper belt over the past 4.5 Gyr.

Several factors have changed since the publication of WDS89. Improved values for the masses and radii of Pluto and Charon (Tholen and Buie, 1990; Elliot and Young, 1991; Null et al., 1993; Young et al., 1994), as well as improved parameters for Charon's orbit, have been obtained (though there is still some controversy over these numbers). Detailed modeling of the expected stable orbits in the Kuiper belt has been performed by Levison and Duncan (1993) and the first two members of the Kuiper belt, 1992 QB_1 and 1993 FW, have been discovered (Jewitt and Luu, 1992; Luu and Jewitt, 1993).

in the following, wc derive improved estimates of cometary impact rates on Pluto and Charon. We show that the Kuiper belt still contributes the largest number of impactors of a given size, but that a significant number of impactors also comes from the inner Oort cloud, a fact missed by WDS89. Moreover, because encounter velocities for inner Oort cloud comets arc almost 5 times higher than for Kuiper belt comets, the inner Oort cloud impacts produce comparable cratering on Pluto and Charon. We also examine the effects of the impacts on the surfaces of the planet and its satellite. Temporal variations in the cratering flux are briefly considered.

Relevant parameters for Pluto and Charon are shown in Table 1. Null et al. (1993) “”- reported a Charon:Pluto mass ratio of 0.0837 $\pm$ 0.0147 based on Hubble Space Telescope imaging of the barycentric motion of the Pluto-Charon system, implying a significantly higher density for Pluto than for Charon. However, Young et al. (1994) performed similar measurements with ground-based telescopes and found a mass ratio of -0.15, which implies roughly equal densities. Until more decisive measurements arc available, the numbers in 'Table 1 assume equal densities for Pluto and Charon. Barring physically unreasonable values of the density, the consequences of future measurement refinements will not be significant to the results presented herein.

Potential Impactors on Pluto and Charon

Three dynamically distinct reservoirs of comets are expected to exist in the outer solar system: the Oort cloud, the inner Oort cloud, and the Kuiper belt (e. g., Oort, 1950; Kuiper, 1951; Weissman, 1991a; Fernandez and Ip, 1991; Duncan et al., 1987, 1988; Weissman, 1993). Each of these contributes to the impactor flux at Pluto.

Two other possible sources of impactors in the Pluto-Charon zone are interstellar comets and Neptune trojans. The flux of interstellar comets passing through the planetary system is constrained on the basis that no comet on a clearly hyperbolic orbit has ever been discovered. Since the flux of interstellar comets appears to be much less than the flux of long-period comets from the Oort cloud, and it will be shown below that the long-period comets are not a significant impactor source, then obviously the interstellar comets must also be insignificant.

Although the well-known 3:2 dynamical resonance between Pluto and Neptune keeps the two planets from making close approaches to each other, the same resonance causes Pluto and Charon to pass regularly through the trojan libration region in the Sun-Neptune system. Holman and Wisdom (1993) showed that stable trojan-type libations are possible in the Sun-Neptune system for time scales of at least 2×10^7 years. One might expect that primordial icy planetesimals may be trapped in these libations as they are for Jupiter. No trojan librators have been discovered beyond the orbit of Jupiter, but such discoveries are observationally difficult because of the distances involved and the likely low albedo of the objects.

Shoemaker et al. (1993) estimated that the population of Jupiter trojans is 3,400 objects larger than 15 km diameter, implying $\sim 5 \times 10^5$ objects larger than 1 km in radius. This is a factor of 1@ to 104 times less than the likely number of potential Kuiper belt and inner Oort cloud impactors of comparable size (see below), and thus, if the number of Neptune trojans are similar, they are probably not a major impactor source. This conclusion may need to be revised as more objects in this region of the solar system are discovered in the future.

Oort Cloud Comet Impact Rates

Everhart (1967) studied observational selection effects for long-period comets and deduced that 8,000 comets brighter than absolute magnitude $H_{10} = 11$ had passed within 4 AU of the Sun over a 128-year period, most of them having been missed because of their intrinsic faintness and/or poor observing geometry. The relationship between the cometary magnitude and mass distributions is uncertain, but one solution (Weissman, 1990) yields a mass of 4 x 10'5 grams for $H_{10} = 11$, corresponding to a radius of 1.2 km if one assumes a nucleus bulk density of 0.6 g cm-^{3}, An alternative mass distribution suggested by Bailey and Stagg (1988) gives a mass of 2.5 x 10'^{4}g (radius = 0.5 km) for $H_{10} = 11$. Everhart found the intrinsic perihelion and brightness distributions for the long-period comets. Combining the perihelion distribution with the derived flux above, one can deduce that 0.1 long-period comets pass within 1 AU of the Sun each year.

The average long-period comet makes -5 returns to the inner solar system (Weissman, 1 979), so -2 of the comets crossing 1 AU per year arc dynamically new. The flux of long-period comets into the planetary region has been simulated by Fernandez (1982) and Weissman (1985), who both showed that the number of cornets passing perihelion per unit AU increases sharply as one moves outward through the planetary region, An example of the perihelion distribution of dynamically new comets from the Oort cloud is shown in Figure 1 (Weissman

1985). As comets are brought into the planetary region by stellar and galactic perturbations, Jupiter and Saturn act as a barrier to comets diffusing to smaller perihelion distances.

'l'he dynamical lifetime of long-period comets at distances much beyond Jupiter's orbit has not been modeled. Comets could be expected to be removed more slowly from the system because of the lesser ability of Saturn, Uranus and Neptune to eject them on hyperbolic orbits. However, since the changes in orbital energy, 1 /a, by planetary perturbations due to those three planets arc substantially less than for Jupiter, a larger fraction of the comets between 7 and 40 AU will return to the Oort cloud where they will likely have their perihelia raised by stellar and galactic perturbations. Thus, the mean dynamical lifetime of those comets may not be much more than the average inside of 7 AU, where Jupiter perturbations dominate.

For the purposes of the calculations in this paper, wc will assume that the perihelion distribution shown in Figure 1 is the distribution for all long-period comets from the outer Oort cloud, and that the average comet makes 10 returns. Because the long-period comets arc only a minor contributor to the impactor flux at Pluto and Charon, this assumption is not critical to estimating the total cratering rate.

Summing the distribution in Figure 1 out to a distance of 39.48 AU (Pluto's orbit) one finds that the Pluto-crossing long-period comet flux is 123 times the flux at 1 AU. Taking the flux of new comets found above and assuming 10 returns per cornet, yields approximately 2.5 x 10^3 long-period comets brighter than $H_{10} = 11$ crossing Pluto's orbit per year. Using the standard Öpik equations (1951, 1976) one can calculate impact probabilities and encounter velocities for a hypothetical sample of near-parabolic comets with the perihelion distribution shown in Figure 1, assuming random orbital inclinations, nodes, and arguments of perihelion.

Based on a random sample of 5 x 10^6 hypothetical comets, the result is that the mean impact probability per perihelion passage for a long-period comet crossing Pluto's orbit is 5.6 x 10^{-14} for Pluto and 1.4 x 10^{-14} for Charon. The rms hyperbolic encounter velocity is 8.2 km s^{-1} for either body. Given the flux estimated above of 2.5 x 10^{3} Pluto-crossing long-period comets per year, the impact rate for comets with $H_{10} < 11$ is 1,4 x 10^{-10} yr^{-1} for Pluto, and 3.5 x 10^{-11} yr^{-1} for Charon. These rates are equivalent to less than one impact on either body over the history of the solar system.

Gravitational focussing is unimportant for long-period comets encountering Pluto and Charon. The impact cross-sections are increased by only 2.1 % and 0.5% at Pluto and Charon, respectively. The flux of long-period comets at Charon's orbit is increased by only 0.13 % by Pluto's gravitational field.

Weissman (1990) has shown that cometary showers from random stars penetrating the Oort cloud, and from encounters with GMC's, will raise the integrated long-period cometary flux at the Earth's orbit by a factor of about three over the history of the solar system. Because the cometary loss cone is filled more at Pluto's distance from the Sun, the net increase there is closer to a factor of two. The result is a total long-period comet impact rate on Pluto of 2.4 x 10^{-10} yr^{-1} and on Charon of 7.0 x 10^{-11} yr^{-1}, still only one or two impacts on either body over the age of the solar system.

Kuiper Belt Comet impact Rates

The stability of orbits in the Kuiper belt has been studied by Levison and Duncan (1993), who showed that orbits with semimajor axes greater than about 42 AU and eccentricities as high as 0.1 were stable for 10^{9} years or more. The first object discovered in the Kuiper belt, 1992 QB_1 has a semimajor axis of 44.4 AU and an eccentricity of 0.107 (Marsden, 1992; although the eccentricity is still somewhat uncertain). The orbit of the second object discovered, 1993 FW, is still uncertain but the semimajor axis is approximately 42.3 AU (Marsden, 1993). Orbital inclinations are 2.2° for 1992 QB_1 and 7.9° for 1993 FW. Thus, both objects are likely in long-lived, stable orbits.

A proposed semimajor axis distribution for Kuiper belt objects, assuming near-circular orbits (Levison and Duncan, personal communication) is shown in Figure 2. Notice that the number of objects increases sharply for semimajor axes between 35 and 42 AU. This increase is even more impressive considering that the data in Figure 2 are plotted on a log scale. Thus, the dynamical modeling indicates that there is a fairly sharp inner edge to the Kuiper belt distribution.

impact probabilities for Pluto and Charon by Kuiper belt comets were calculated using the standard Opik equations (1951, 1976). We modeled the Kuiper belt comets by assuming circular orbits with inclinations $< 10°$, and placing a sharp inner "edge" in the semimajor axis distribution at a range of heliocentric distances between Pluto's perihelion and aphelion. Results arc shown in Table 2. For reasonable values of the inner edge distance, 36 to 44 AU, the impact probability and encounter velocity varies slowly with heliocentric distance. The only “”- large variations occur when the edge is placed close to Pluto's aphelion distance, where the Kuiper belt comets are only shallowly crossing Pluto's orbit. However, placing the edge of the semimajor axis distribution of the Kuiper belt comets at that distance is clearly in conflict with the dynamical modeling results of Levison and Duncan (1993).

The impact rate of Kuiper belt comets is thus determined primarily by their total numbers, and not by the precise shape of the semimajor axis distribution. For the purpose of further calculations, we assume that the edge is at 40 AU. Thus the mean impact probability for a Pluto-crossing Kuiper belt comet on Pluto is 1.7 x 10^{-13} per revolution, or 6.0 x 10^{-16} yr^{-1}. The corresponding probabilities for Charon arc 0.30 x 10^{-11} pcr revolution and 1.0 x 10^{-16} yr^{-1}. The rms hyperbolic encounter velocity for either body is 1.7 km s^{-1}.

At this encounter velocity, gravitational focussing plays a larger role, contributing an additional 49% to the physical cross-section of Pluto, and 13% additional for Charon. Gravitational focussing by Pluto at Char-on's orbit adds another 3%.

The number of Kuiper belt comets versus heliocentric distance is not known. A population of 10^8 to 10^{10} objects has been estimated in order to supply the observed flux of short-period comets, assuming that short-period comets need to be resupplied at a rate of about 10^{-2} pcr year (Duncan et al., 1988). If one assumes a population of 109 objects in near-circular orbits, uniformly (distributed between 40 and 100 AU, then there will be 1.7 x 107 objects per A U . Thus, - 1,6 x 108 of those objects will be in Pluto-crossing orbits, since Pluto's aphelion distance is 49.31 AU. The expected impact rate of Kuiper belt comets on Pluto will therefore be 9.3 x 10^{-8} yr^{-1}, or about 420 impacts over the age of the solar system. For Charon the corresponding numbers are 1.6 x 10-8 yr^{-1} and 70 impacts over the age of the solar system.

The Kuiper belt is too deep in the Sun's gravitational potential well to be significantly perturbed by external sources such as random passing stars or GMC's (Stern, 1990). '1'bus, cometary showers from the Kuiper belt are not likely. However, the cometary flux earlier in the solar system's history was likely higher simply because the inner edge of the belt had not yet been eroded away by Neptune perturbations. Assuming that the inner edge of the belt might have extended in as far as just beyond Neptune's orbit, say 32 AU, the impact rate in the early solar system may have been a factor of -1,8 higher than the estimate above.

Inner **Oort Cloud** Comet Impact Rates

There are no observations of comets in the inner Oort cloud and thus one must rely on theoretical modeling to give orbit distributions and population. As noted in the Introduction, Duncan et al. (1987) showed that the inner Oort cloud population is about five times that of the outer, dynamically active Oort cloud, or about 5 x 10'2 comets (Weissman, 1991). These orbits have been largely, though not totally, randomized by stellar and galactic perturbations. If we assume that they arc totally randomized (Duncan et al., 1987 showed that the orbits in the inner cloud were fairly well dispersed in eccentricity though not in inclination), then the perihelion distribution of the inner Oort cloud comets in the planetary region is given by Hills (1981)

$$f = 2q/a \ (1 - q/2a) \approx 2q/a \quad \text{for } q << a \tag{1}$$

where f is the fraction of the population with $q < a$, q is the perihelion distance, and a is the semimajor axis. Given a population of S x 10^{12} comets and a typical semimajor axis in the inner Oort cloud of 3×10^3 AU, the density of perihelia is 3.3×10^9 AU^{-1} in the planetary region. Because inner Oort cloud comets have typical periods of 1.6×10^5 years, the flux versus time is 2,0 x 10^4 AU^{-1} yr^{-1}.

Under normal conditions, i.e., no major perturbcrs, inner Oort cloud comets do not penetrate into the inner planets region. 'l'heir aphelia are too deep in the Sun's gravitational well for thcm to be perturbed significantly in perihelion distance in one orbit. They may diffuse across the orbits of Uranus and Neptune but not likely that of Jupiter and Saturn. The question then is, where is the inner "edge" of the inner Oort cloud perihelion distribution located? Because they arc subject to some external perturbations, the edge for the inner Oort cloud comets will likely not bc as sharp as it is for the Kuiper belt comets.

Dynamical studies by Levison and Duncan (1993) and Holman and Wisdom (1993) showed that the orbits of test particles between the outer planets become planet-crossing in less than 10^9 years. Once they are planet crossing, these objects are typically ejected from the solar system on t imc scales of 1 to 2 x 10* years (Wetherill, 1975). Many of these comets, in particular those from the Uranus-Neptune zone, will be ejected to eccentric orbits in the inner Oort cloud. Eventuall y the rate of cometary ejections will be balanced by comets diffusing back into the planetary region from the inner Oort cloud, and a steady-state perihelion distribution will be achieved. Unfortunately, detailed dynamical modeling of that process has not yet been performed,

Because of the relatively short dynamical lifetime of Uranus and Neptune-crossing comets relative to the age of the solar system, we will assume that the inner "edge" of the inner Oort cloud perihelion distribution must be at or somewhat beyond Neptune's orbit. Again, because of the slow variation of impact probability and encounter velocity with heliocentric distance, the precise location of the edge. is not important, so long as it is not close to Pluto-grazing orbits. That seems fairly unlikely.

Using the Opik equations one can again estimate the impact probability and encounter velocity of inner Oort cloud comets on Pluto and Charon. Random orbital inclinations and eccentricities are assumed. Results are shown in '1'able 3 for different values of the inner edge location. As expected, the mean impact probability varies slowly with the position of the edge. The rms impactor velocity is 8.2 km s-l, independent of q_{min}, For purposes of further calculations, we will assume that the edge is at 36 AU, i.e., that the steady-state perihelion distribution of the longer period comets from the inner Oort cloud penetrate somewhat closer to Neptune, than the shorter period, Kuiper belt orbits. This is expected based on the action of externa perturbers and the longer orbital periods of the inner Oort cloud comets (which makes thcm less susceptible to Neptune perturbations).

Using the inner Oort cloud flux of 2.0 x 10^4 AU^{-1} yr^{-*} comets found above, and the values in Table 3 for the inner edge of the inner Oort cloud at 36 AU, the resulting impact rate cm Pluto is 3.2 x 10^{-8} yr^{-1}, or -144 impacts over the age of the solar system. For Charon the corresponding rates are 8.2 x 10-9 yr^{-1} and -37 impacts. These numbers are about one-third of the number of Pluto impacts estimated in the previous section for Kuiper belt comets, and about one-half the number of Charon impacts. Because of the lower encounter velocities for Kuiper belt comets relative to inner Oort cloud comets, gravitational focussing by Pluto has a significant effect in increasing the number of Kuiper belt comet impacts on the planet.

Note, however, that the inner Oort cloud comets encounter Pluto and/or Charon with an rms velocity which is 4.8 times that for Kuiper belt comets, or about 23 times the kinetic energy per unit mass. If the cumulative cometary mass distribution has a slope of about 1.7 and extends down a factor of 23 in mass (i.e., a factor of 2.8 in radius), then there will be a total of 2.9 x 10^4 inner Oort cloud impactors that can produce the craters of comparable size as the -420 Kuiper belt impactors estimated in the previous section, For Charon, similarly sized craters are obtained for -7.4 x 10^3 inner Oort cloud comets as for the -70 Kuiper belt comets estimated previously. Thus, the inner Oort cloud is also a dominant contributor to the impactor flux on Pluto and Charon, if it exists in the numbers that have been estimated to date, and with a perihelion distribution extending inside of Pluto's scmimajor axis.

Cratering on Pluto and Charon

Using the impactor fluxes and encounter velocities estimated in the previous sections, one can estimate the size and surface coverage fraction of cometary impact craters on Pluto and

Charon. Following Holsapple (1993), the diameter of a hemispherical craters is given by

$$D = 1.26\ d\ (A\ \rho_{impactor}/\rho_{target})^{1/3}\ (1.61\ g\ d\ /\ v_i^2)^{-\alpha/3} \qquad (2)$$

where d is the spherical equivalent impactor diameter, ρ is the density, g is the surface gravity of the target, vi is the impact velocity, and A and α are constants which depend on the mechanical properties of the target surface material. We usc Holsapple's (1993) values of A and α for competent water ice, 0.2 and 0.6, respectively. For comparison, Holsapple gives A = 0.24 and $\alpha = 0.51$ for sand; adopting these values would not substantially change the results given below.

For Pluto and Charon, g = 60 cm S^{-2} and 30 cm S^{-2}, respectivel y. The impact velocity, vi $= (U^2 + v_{esc}^2)^{1/2}$ where U is the hyperbolic encounter velocity and v_{esc} is taken from the values in Table 1. We also adopt $\rho_{impactor}$ = 0.6 g cm^{-3} and ρ_{target} = 1.0 g cm^{-3}, which is probably a good estimate for the surface densities of both bodies. The modest dependence of D on ρ makes the results insensitive to uncertainties in the choice of surface or bulk density. 1 'or example, if the actual density ratio of the impactor to surface material is a factor of two different from the assumed value, the resulting crater diameter would change by only 26%. Similar] y, the weak dependence of D on g and v_{esc} ensures that the existing uncertainties in the radius of Pluto and the density of Charon cannot induce errors in D exceeding 5 %. Estimated crater diameters for Kuiper belt and inner Oort cloud impactors, using Equation (2), are shown in '1'able 4.

The results in 'l'able 4 indicate that craters produced by typical inner Oort cloud impactors will be -1.7 times larger in diameter than craters produced by typical Kuiper belt impactors of the same size, because of the higher mean encounter velocity. These results also indicate that if the mechanical properties of the upper few kilometers of Pluto's surface is like

Charon's, then Charon's lower gravity will result in craters - 10'% larger than on Pluto,

Craters which penetrate Pluto's volatile veneer or crust may excavate water icc to the surface, where it will remain until covered by seasonal frost migration. Another interesting result comes from calculating the mass of the transient vapor cloud produced by comet impacts on a water-ice surface. This quantity can bc crudely estimated by comparing the impactor energy pcr unit mass with the sublimation energy of the surface ice,

$$M_{vapor} = 1/2 \ v_i^2/\epsilon_c \tag{3}$$

where CC is the critical specific energy for vaporization of the target material. Assuming a water icc surface and a normal impact (oblique impacts produce even more vapor because of jetting), $\epsilon_c = 6 \times 10^{11}$ J/g, and a typical Kuiper belt impactor would generate -2 x 102 g of vapor per gram of impactor. In contrast, at the mean inner Oort cloud impactor velocity, $\sim 6 \times 10^{-1}$ g of vapor can bc produced per gram of impactor. Cometary impacts with mass > 9×10^{15} g (radii > 1.5 km) from the inner Oort cloud should produce transient atmospheres comparable to, or even substantially exceeding the -5×10^{15} g mass of Pluto's present, perihelion atmosphere. Kuiper belt impacts would produce an atmospherically significant mass of vapor only for impactors with masses > 2×10^{17} g (radii > 4.4 km).

By comparing the ratio of target gravitational stress (ρ_{target} g) to the target material yield strength Y, one finds that the critical crater diameter for the cratering transition from strength scaling to gravity scaling occurs at less than 2 km on both Pluto and Charon, assuming the surface is made of water ice (Y ≈ 107 erg cm^{-3}). In analogy to the icy Saturnian and Uranian satellites, the water ice assumption is likely to be very good on Charon. On Pluto, however, it is possible that the surface consists of a deep layer of weak, volatile snows (e. g., N_2, CH_4), which could push the transition diameter substantially higher.

Finally, there is the issue of the surface crater covering fraction. We assume that the ejecta blanket around a typical crater extends -1 crater diameter beyond the rim of the crater. Thus, the number of craters required to completely cover the surface area of Pluto (1.75×10^7 km^2) is $2.5 \times 10^6/D^2$, where D is the typical crater diameter in kilometers (neglecting overlap). Similar] y, on Charon one requires $\sim 6.5 \times 10^5/D^2$ impacts to cover the surface.

Based on the impactor speeds and sizes given above, the predicted 420 Kuiper belt impacts on Pluto and 70 Kuiper Belt impacts on Charon will cover -3 to 22% of these bodies, if the impactor diameters are between 2,4 and 10 km. If the impactors have typical diameters of 1 to 3 km, the covering fraction of craters will be -1 to 3%.

For inner Oort cloud produced craters, the expected cratering flux is - 1/3 to 1/2 that for the Kuiper belt comets, but the higher impact energies produce crater diameters covering about three times as much area. Thus, the cratering coverage from inner Oort cloud comets is nominally predicted to be comparable to Kuiper belt comets of the same size. Together, the craters plus their immediate ejecta blankets would cover -14 to 44% of the total surface area of Pluto and Charon, not enough for saturation.

Because of comet showers from the inner Oort cloud and a higher Kuiper belt population in the past, the time integrated flux of impactors may be up to twice the current estimated values. This would still likely not be sufficient to accomplish cratering saturation, even if no resurfacing events have occurred.

Discussion

We have estimated impact rates on Pluto and Charon from the three major cometary reservoirs, and showed that the cratering is dominated by Kuiper belt and inner Oort cloud comets. The total number of predicted impacts are probably insufficient to have saturated the surface areas of these two bodies. The crater densities on Pluto and Charon may be closer to that of the lunar maria than to the heavily cratered surfaces seen on many outer solar system satellites,

The Pluto-Charon system is the only completely tidally evolved planet-satellite system in the solar system: Pluto rotates with precisely the same period as Charon's orbital motion and the two always show the same face towards each other. The tidal evolution leading to this state may have dissipated considerable energy within the two bodies, and this may be reflected in resurfacing events which have destroyed some of their past cratering history. That tidal evolution likely occurred rather rapidly after the Pluto-Charon binary formed. Although it is suspected that the binary formed early in the solar system's history, there is no way at present to confirm that assumption. If the Pluto-Charon binary was produced by a collision, then it is possible that debris from the collision also contributed to the early cratering history.

Spectroscopic observations have detected a different apparent surface composition for Pluto and Charon, with the former being covered by methane and nitrogen ice, and the latter by water ice. Whether these differences are simply thin surface veneers or substantial compositional differences cannot be answered at this time. If the underlying crustal material is different for the two bodies, then crater retention ages due to ice relaxation may be different, and this too may contribute to different appearances for the two bodies.

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Table 1. Pluto-Charon System **Parameters**

	Pluto	Charon	
Radius - km	1,180	603	Minis et al. (1993) Elliot and Young (1991)
Mass* - g	1.25X 10^{2s}	1.67x 10^{24}	
V_{esc}** - km s^{-1}	1.189	0,608	
Orbit period - days		6.38725	Tholen and Buie (1990)
Orbit radius - km		19,405	Null et al. (1993)
Orbit velocity** - km s^{-1}		0.221	
V_{esc} at Charon's orbit** - km s^{-1}		0.293	

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* Masses assume equal density and total system mass of 1.42x 10^{25} g (Beletic et al., 1989; result scaled to orbit radius of Null et al. 1993)

** Calculated from other parameters

Pluto's orbit:	J2000 (Seidelmann, 1992)
Semimajor axis - AU	39.4816
Eccentricity	0.248808
Inclination - degrees	17.14175

Table 2. Mean Impact **Probabilities** and Encounter Velocities for **Kuiper** Belt Comets

a_{min} - AU	34	36	38	40	42	44	46	48
Pluto								
p - per orbit (x 10”’^{3})	1.5	1.5	1.6	1.7	1,9	2.2	2.7	4.1
p - yr^{-1} (x 10-’^{6})	5.3	5.3	5.4	S.6	6.0	6.7	8.1	12.2
Charon								
p - per orbit (x 10^{-13})	0.26	0.27	0.28	0.30	0.33	0.37	0.45	0.67
p - yr^{-1} (x 10^{-16})	0.93	0.94	0.95	0,97	1.0	1.1	1.3	2.0
U_{rms} - km S^{-1}	1.8	1.8	1.7	1.7	1.6	1.6	1.5	1.4

(same for Pluto and Charon)

Table **3.** Mean **Impact Probabilities and Encounter Velocities** for Inner Oort **Cloud** Comets

q_{min} - AU	32	34	36	38	40	42	44
Pluto							
p - per orbit (x 10^{-3})	1.1	1.1	1.2	1.3	1.4	1.6	1.9
Charon							
p - per mbit (x 10^{-3})	0.27	0.29	0.31	0.33	0.36	0.41	0.48

'J'able 4. **Estimated Crater Diameters**

Kuiper belt impactors	U = 1.7 km s^{-1}	
	Pluto	Charon
V_{impact} -km s-'	2.1	1.8
Impactor diameter - km	Crater diameter -km	
1,0	3.3	3.6
2.4	6.6	7.3
10	21	25

Inner Oort cloud Impactors	U = 8.2 km s^{-1}	
	Pluto	Charon
V_{impact} - km s“'	8.3	8.2
Impactor diameter - k m	Crater diameter - km	
1.0	5.7	6.7
2.4	12	13
10	36	42

Figure captions

Figure 1. Perihelion distribution of dynamically new, long-period comets from the Oort cloud, as found by Weissman (1985). Jupiter and Saturn serve as a dynamical barrier to the diffusion of cometary perihelia into the inner planets region.

Figure 2. Proposed semimajor axis distribution for Kuiper belt comets by Levison and Duncan (personal communication), assuming circular orbits. The number of Kuiper belt comets increases sharply between 35 and 42 AU. The dashed curve assumes a solar nebula accretion disk with density decreasing as r^{-2} with heliocentric distance.

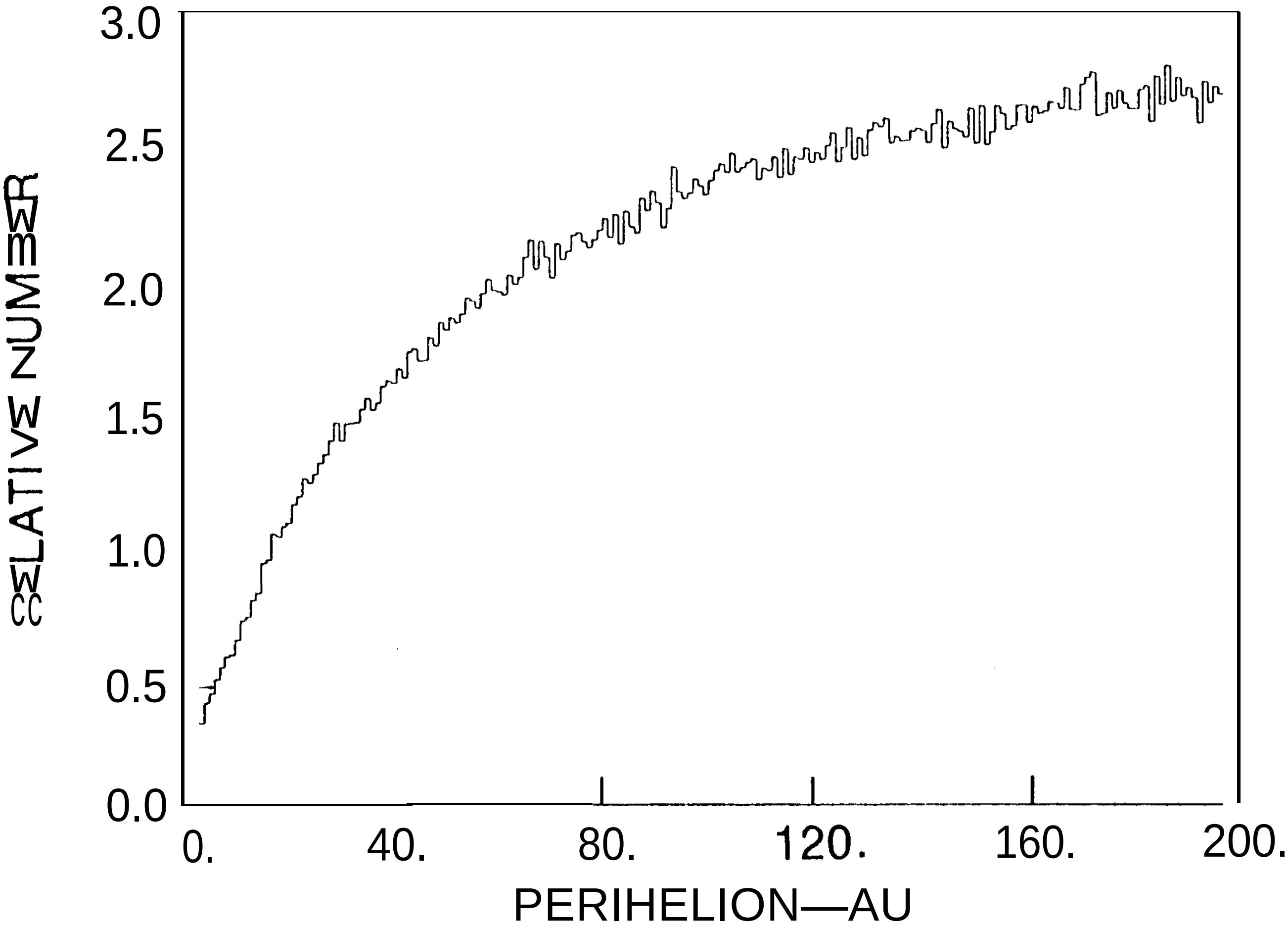

Figure 1.

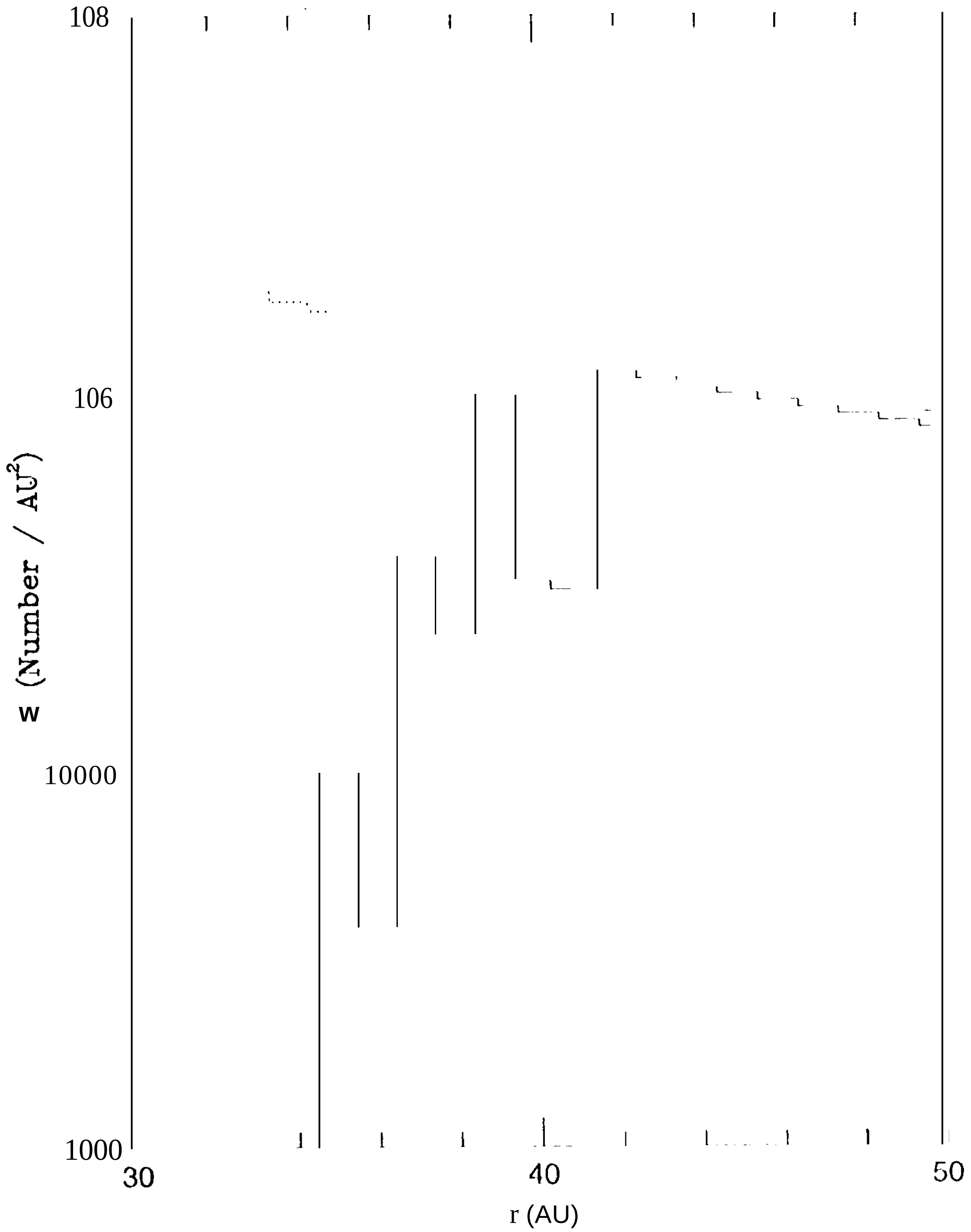

Figure 2.